

# Over Saturation in SiPMs: The Difference Between Signal Charge and Signal Amplitude

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## Abstract

A recent report on the over saturation in SiPMs is puzzling. The measurements, using a variety of SiPMs, show an excess in signal far beyond the physical limit of the number of SiPM microcells without indication of an ultimate saturation. In this work I propose a solution to this problem. Different measurements and theoretical models of avalanche propagation indicate that multiple simultaneous primary avalanches produce an ever narrower and faster signal. This is because of a speed-up of effective avalanche propagation processes. It means that SiPMs, operated at their saturation regime, should become faster the more light they detect. Therefore, signal extraction methods that use the amplitude of the signal should see an over saturation effect. Measurements with a commercial SiPM illuminated with bright picosecond pulses in the saturation regime demonstrate that indeed the rising edge of the SiPM signal gets faster as the light pulses get brighter. A signal extractor based on the amplitude shows a nonlinear behavior in comparison to an integrating charge extractor. This supports the proposed solution for the over saturation effect. Furthermore I show that this effect can already be seen with a bandwidth of 300MHz, which means that it should be taken into account for fast sampling experiments.

**Keywords:** Over Saturation, Signal Extraction, Avalanche Breakdown, SiPM, GAPD, Geiger Avalanche Diode

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## 1. Introduction

Silicon Photomultipliers (SiPMs) are novel photo detectors designed to detect weak light signals and are used for a large variety of applications. Each SiPM consists of a matrix of avalanche diode cells with a common readout. The absorbed photons produce hole-electron pairs in the depleted region. Then the carriers are accelerated in the reverse bias electric field and ionize more carriers in an avalanche breakdown process. The avalanche diodes are operated in the Geiger regime.

Recently, Gruber et al. [1] reported on the over saturation in SiPMs. Their measurements showed an increase in signal beyond the physical limit of the number of SiPM microcells without indication of an ultimate saturation. They speculated that simultaneous avalanches could induce a higher charge signal. Here, however, I want to propose a physically more plausible model.

Theoretical models of avalanche propagation [2] suggest that multiple simultaneous primary avalanches produce an ever narrower and faster microcell signal. This

results from the speed-up of effective diffusion processes. When a photon triggers an avalanche in an SiPM microcell, it grows vertically and laterally and reaches a maximum lateral size of about  $10\mu\text{m}$  after less than a nanosecond. This size is usually smaller than the microcell size [3], Therefore the time resolution depends on where in the SiPM microcell the avalanche was triggered [4]. Popova et al. [2] indeed demonstrate that single microcells produce a narrower, higher amplitude pulse when exposed to bright light flashes. Nevertheless they observe that the charge within the pulses stays the same. Such a behavior can be understood if the charge released is constant and the microcell gets faster, see Fig. 1.

Furthermore it means that the entire SiPM detecting bright, saturating sub-nanosecond light flashes should become intrinsically faster the more light it detects. This is because every single microcells get faster the more simultaneous photons they are exposed to.

This suggests that charge signal extractors should see normal saturation, while amplitude signal extractors should see over saturation — a signal beyond the number of physical microcells. Gruber et al. reported

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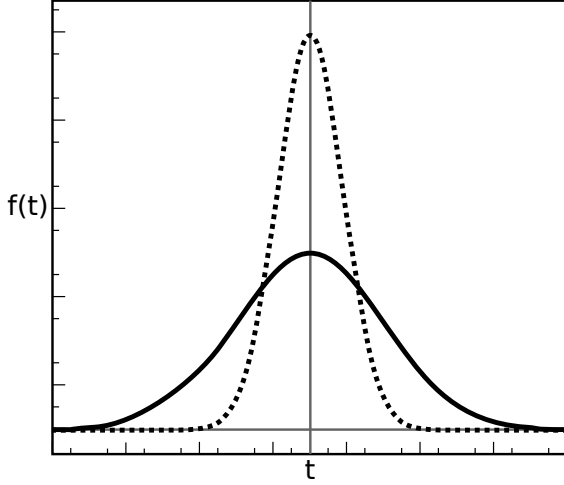


Figure 1: A schematic of two signals. Both have the same area under the curve (corresponding to the charge), but have different amplitudes, depending on their rise and fall time.

that they indeed used such an amplitude extractor (the height of the maximum), to reduce the effect from after-pulsing and late cross-talk. They claim to have observed no change in the shape of the signal, yet this is what I think is responsible for the over saturation effect they observed.

## 2. Methods and Materials

To readout the undistorted SiPM signals a custom SiPM board, without preamplifier and without decoupling capacitor, is built, see Fig. 2. Its signals are fed directly into the measurement oscilloscope. As the measurements are in the saturation regime, the signals from the SiPM are large and the intrinsic SiPM amplification is sufficient. Also, a preamplifier could distort the measurement. The SiPM used is a S10362-33-100C MPPC from Hamamatsu with 900 microcells. Another MPPC of the same model is used for verification of the results. The bias is set to the data sheet value of  $\sim 70\text{V}$  at room temperature. A Picoquant diode laser head at 782 nm with a pulse width of few  $\sim 10\text{ps}$  illuminates the SiPM via an optical fiber and an optical diffuser. The laser head intensity can be continuously adjusted. The fiber, the diffuser, the SiPM and the bias board are all placed in a dark box. The fast signals are recorded with a LeCroy 2GHz, 10GS/s 204MXi-A sampling oscilloscope. Each waveform is averaged over 1000 triggers from the pulsed light source which is operated at 1kHz to have enough time for the SiPM to recharge.

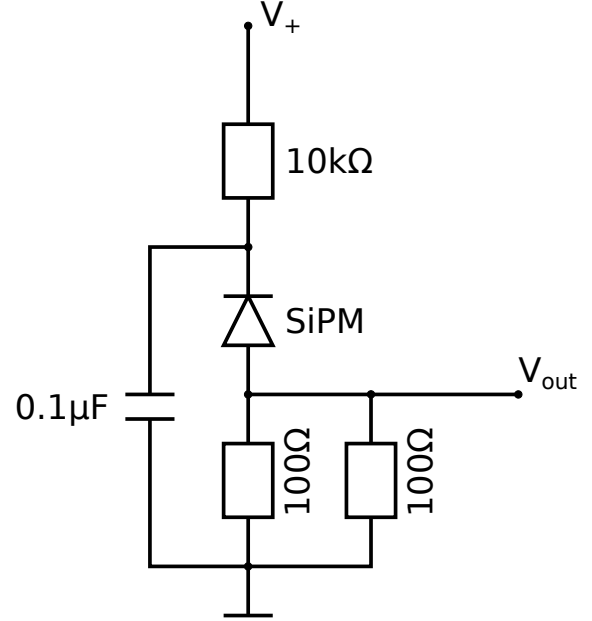


Figure 2: The schematic of the SiPM board. In order to minimize the distortion of the signal, no preamplifier and no decoupling capacitor are used.

As the signals are not amplified, it is unfeasible to calibrate the signals via the single photoelectron spectrum. Therefore a calibration via the excess noise factor is done. For this I use a Poisson source of photons with a mean number of detected photons per pulse  $\mu$  and assume a geometric chain process cross-talk model with cross-talk probability  $p$ , a random number of detected photons  $N$ , a random number of detected SiPM breakdown cells  $X \geq N$ , and an excess noise factor  $ENF$  defined as the loss of signal-to-noise ratio

$$ENF = \frac{E^2[N]/\text{Var}[N]}{E^2[X]/\text{Var}[X]}. \quad (1)$$

It follows [5] that the gain  $g$ , defined as proportionality constant between measured signal  $Q$  and number of cells in breakdown  $X$

$$Q = gX, \quad (2)$$

can be measured as

$$g = \frac{\text{Var}[Q] \frac{1-p}{E[Q]}}{1+p}. \quad (3)$$

The amplitude extractor gain  $g_{amp.}$  was measured at operating voltage using 1000 low light intensity pulses of  $\sim 30$  detected photons/pulse as saturation has to be negligible for this measurement. The charge extractor gain is estimated by applying a linear model to a part of the

data where both extractors are proportional to each other (see Sec. 3). The last step of the calibration is to apply it to the mean measured signal  $E[Q']$ , in order to determine the number of mean detected photons  $\mu$  in a pulse. With the simple geometric chain cross-talk model, the result is

$$\mu = \frac{E[Q']}{g}(1 - p). \quad (4)$$

The SiPM under study has  $p \sim 0.1$  cross-talk at operating voltage and I estimate the accuracy of measuring  $\mu$  to  $\Delta\mu/\mu \sim 10\%$

### 3. Results and Discussion

Fig. 3 shows the different waveforms as measured with the oscilloscope. The measurement consists of a series of 14 intensity settings with rising brightness from about 287 detected photons per laser shot to about 755 detected photons per laser shot. The waveforms are all pedestal subtracted. One can see that the rising edges get slightly steeper, the brighter the initial light pulse is. A measurement with a second SiPM of the same type shows the same behavior.

To quantify this result, Fig.3 also shows a comparison of an amplitude extractor and an integrating (charge) extractor. They are proportional in the lower count regime. Both extractors show rising signals, as the physical saturation limit of 900 (microcells) is not quite reached. Yet, in the saturation regime and assuming the over saturation behavior comes from the speeding-up of the avalanche diffusion, one would expect that the signal from the amplitude extractor should saturate slower than the integrating charge extractor. This non-linear effect is observed. The influence of afterpulsing on the integrating charge extractor can not mimic such a behavior as its effect is to increase the charge measurement, opposite to what is observed. The figure also shows a measurement conducted with a 300MHz FIR low pass filter on the oscilloscope. This shows that typical fast sampling experiments need to take this effect into account (depending on the dynamic range of their digitization).

Diffusion of multiple simultaneous avalanches can further explain how a lower bias leads to more over saturation [1], as lower biased cells are slower [2] and therefore the effect of two simultaneous avalanches is stronger. It may also explain how SiPMs from the same manufacturer, but different microcell size, show different over saturation behavior [1]. This is because the avalanche has a limited size smaller than a microcell. Therefore different microcell geometries have different timing behavior.

### 4. Conclusion

Multiple simultaneous avalanches make the microcells and in turn the whole SiPM faster, which can explain the previously observed over saturation effect in SiPM. In this work I report on measurements with a commercial SiPM from Hamamatsu, which is illuminated with bright picosecond pulses in the saturation regime. The measurements indicate that the rising edge of the SiPMs gets faster and that a fast signal extractor based on the amplitude shows a nonlinear behavior in comparison to an integrating charge extractor, supporting the proposed explanation. The effect can already be seen with a low pass bandwidth filter of 300MHz. This means that it should be taken into account for fast-sampling experiments.

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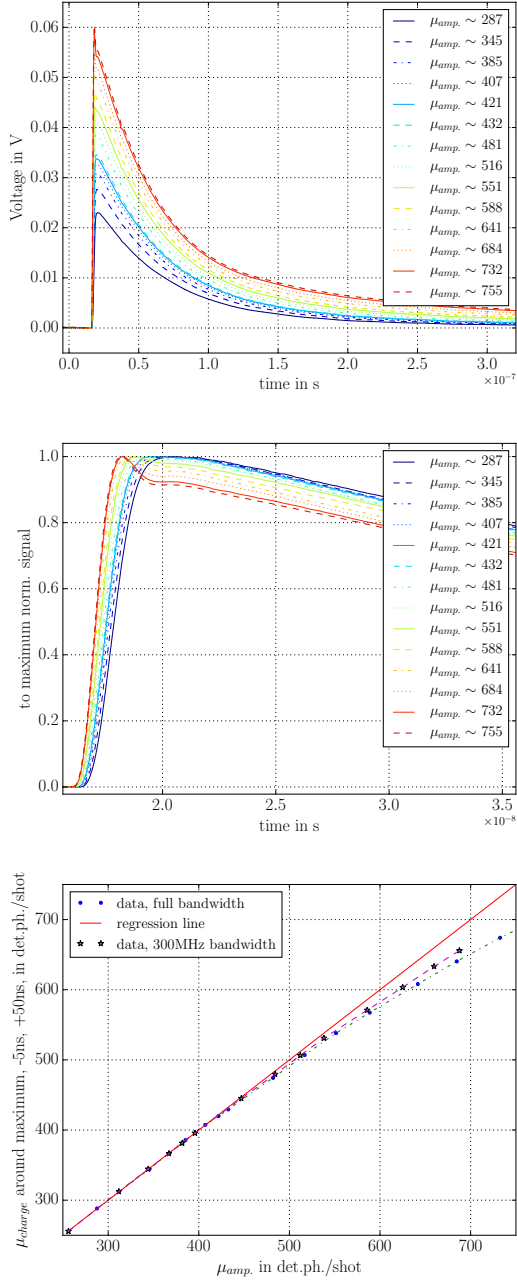


Figure 3: Top: The oscilloscope signals with full bandwidth. Every waveform is averaged and pedestal subtracted. The light pulse intensity is increased from  $\mu_{amp.} \sim 287$  detected photons per laser shot to  $\mu_{amp.} \sim 755$  detected photons per laser shot as measured with the amplitude extractor. Middle: A zoom into the rising edge of the same oscilloscope signals. They are normalized to their maxima. One can see that the rising edge gets steeper. Bottom: A comparison of an integrating (charge) signal extractor to an amplitude extractor. The amplitude extractor uses the pedestal subtracted maximum, is calibrated with Eqn. 3 & 4, and detects  $\mu_{amp.}$  photons per pulse. The charge signal extractor uses an integration window of  $-5\text{ns}$  to  $+50\text{ns}$  around the maximum. In order to calculate the charge extractor gain  $g_{charge}$ , a linear model is fitted to the first four data points on each dataset, where both extractors are proportional. This gain is then used to calculate  $\mu_{charge}$ .